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LATERALIZED DIVISION OF ATTENTION IN THE COMMISSUROTOMIZED AND INTACT BRAIN*

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Abstract—The degree to which voluntary maintenance of independent attentional systems in left and right hemispheres during lateralized double simultaneous performances is possible for prolonged periods was assessed in five complete commissurotomy patients, two partial commissurotomy patients and eight normal subjects. Subjects performed a unimanual tactual sorting task as well as bimanual sorting tasks requiring (1) the same, (2) different or (3) opposite simultaneous decisions by left and right hemispheres. Normals were also given additional practice sessions with the same tasks in an effort to determine limitations in the capacity for dual processing. The results suggest that the cerebral commissures force the two hemispheres to work together and maintain attentional unity in the intact brain. Practice increases the capacity for simultaneous processing in normals, but this enhancement is most readily interpreted as the result of automation of performance decreasing the need for attentional supervision rather than as a division of the normal unity of focus in the intact attentional system.

INTRODUCTION

FOLLOWING section of the cerebral commissures, patients have shown identical reaction times whether responding to a unitary visual discrimination task or to two such tasks presented simultaneously in the left and right fields, whereas normal controls show large decrements in reaction time to the dual stimuli [1]. Split-brain monkeys also have been shown to learn contradictory visual tasks concurrently [2] and to process more information than normals when simultaneous stimuli are presented to the two hemispheres [3]. In a recent study involving bimanual tactual sorting tasks, commissurotomy patients demonstrated dual attentional processes over long periods in which spontaneous reversals in cognitive set resulted in mutually opposing sorting decisions on left and right proceeding simultaneously without loss of response speed or accuracy [4]. In the absence of the corpus callosum, then, it is possible for separate attentional mechanisms to proceed simultaneously in each disconnected hemisphere.

Results such as the foregoing suggest that the commissures act to insure unity of attention and raise the question of the extent to which dual cognitive processing in left and right hemispheres is possible in the intact state. The ability of normal subjects to sustain accurate performance on two tasks simultaneously has been demonstrated in some studies [5, 6, 7], while in others interference between two or more simultaneous inputs is indicated [8, 9]. The capacity to process multiple inputs is reported to be greater when stimuli or responses

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involve different sense modalities [6] or are very dissimilar [10]. The degree of interference between simultaneous tasks is also related to ease of task performance [11], which is to some extent dependent on familiarity [12]. Double concurrent performances that proceed readily for commissurotomy subjects when the two tasks can be lateralized to separate hemispheres are found to cause severe disruption when both tasks are processed in the same hemisphere [13, 14]. In normal subjects, simultaneous tasks have also been reported to interfere more when processing is in a single hemisphere [15].

To further investigate whether double performance in normals may be aided by allocation to separate hemispheres, the present study compares commissurotomized and normal subjects with respect to the capacity for division of voluntary attention between two simultaneous prolonged and attention-demanding tasks involving lateralized input and performance with left and right hands. The degree to which practice may enhance the capacity for simultaneous processing in normals was also tested with reference specifically to whether improved performance may involve a right/left division of attention similar to that seen in commissurotomy subjects. The results are consistent with the view that the two hemispheres are generally forced to function and attend as a unit in the presence of the commissures.

METHODS AND RESULTS

Subjects

The study was conducted with five commissurotomy patients (A.A., L.B., N.G., N.W., and R.Y.) with presumed complete surgical section of the corpus callosum and two partial commissurotomy patients (N.F. and D.M.) in whom the posterior third of the corpus callosum was left undivided. The case histories and descriptions of the surgery are presented in detail elsewhere [16, 17, 18]. Also tested were eight normal right-handed adults with a mean age of 30 years and a mean of 17 years of schooling.

Experiment I: Procedure

Four variations of a tactual sorting task were presented. For all task conditions with a single exception to be noted below, the subject sat wearing a blindfold at a table directly in front of three stationary plastic containers. One was centered horizontally between the other two which were positioned vertically in front of the subject's left and right hands. The two side containers were divided into identical top and bottom compartments. The central container was filled with two kinds of beads of similar overall size ($\frac{3}{8}$ in. in diameter) and weight (0.5 g) with one being spherical and smooth and the other cylindrical with rough ridges. A more detailed description of the equipment is included in an earlier report [4]. Subjects sorted beads by transferring them from the central container to the side compartments for an uninterrupted 3-min period under each of the following four conditions:

Unimanual. Subjects were instructed to place spheres in the top compartment and cylinders in the bottom compartment of the right side container with their right hands. After two trials manually guided by the examiner to assure proper tactual localization of the boxes, subjects practiced to a criterion of six consecutive correct trials. They were then told to sort as fast as they could without errors and without pause for a 3-min period. The procedure was identical for left-handed unimanual sorting except that beads were dropped into the left side container with cylinders placed in the top compartment and spheres in the bottom. One half of the subjects sorted first with the right hand and the other half began with the left. Following completion of each 3-min period, the examiner counted the number of correct and incorrect beads in each compartment.

Bimanual-same. Subjects were instructed to sort with both hands working concurrently, placing spheres in the top and cylinders in the bottom of the right and left side containers with the right and left hands, respectively. Instructions specifically stressed simultaneity rather than alternation of hand movement. In this task, as in the other two bimanual sorting conditions, practice to a criterion of six consecutive correct trials was conducted first with right and left hands unimanually and then both hands working together. This was followed by the timed 3-min bimanual sorting period.

Bimanual-reverse. Under this condition, subjects sorted simultaneously with the two hands operating under opposite instructions. The right hand sorted spheres into the top compartment and cylinders into the bottom of the right side container while the left hand placed cylinders in the top and spheres in the bottom of the left side container.

Bimanual-different. This task condition utilized slightly modified equipment. Placed between the two side containers were two central containers, one for each hand. The right hand sorted from a central container filled with $\frac{5}{16}$ in. hex nuts and $\frac{1}{4}$ in. wing nuts, each weighing 5 gm. Subjects were instructed to place hex nuts in the top

compartment and wing nuts in the bottom of the right side container. At the same time, the left hand sorted from a central container holding the beads described earlier, with subjects told to place spheres on top and cylinders on bottom of the left side container. Test procedure was identical to that of the other bimanual tasks.

The four task conditions were administered in three different test sessions which were separated from each other by at least 48 hours. All subjects performed the tasks in the following order: Bimanual-reverse and Unimanual in Session 1, Bimanual-same in Session 2 and Bimanual-different in Session 3.

Experiment I: Results

Figure 1 shows the right- and left-handed sorting rates of normal subjects, complete commissurotomy patients and partial commissurotomy patients on the four sorting conditions of Experiment I, with the rates being expressed as objects sorted per minute. In the normal controls and partial commissurotomy patients, bimanual sorting rates for the two

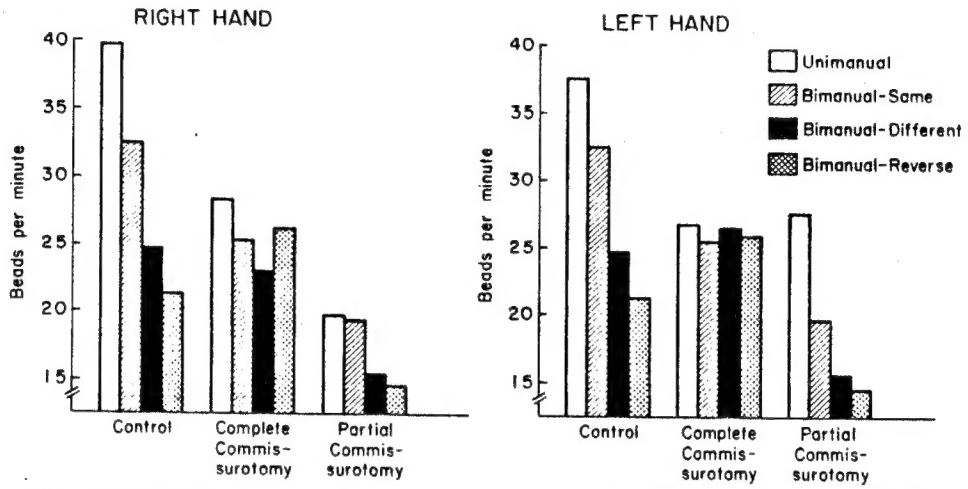

FIG. 1. Right and left-handed sorting rates of complete commissurotomy, partial commissurotomy and normal control subjects for four task conditions of Experiment I.

hands were identical to each other reflecting bimanual synchrony. This is not the case for the complete commissurotomy group since several of these patients (N.G., N.W., and R.Y.) sometimes sorted at different rates with two simultaneously operating hands, an occurrence which has been noted previously [4, 13].

The most striking finding evident from Fig. 1 is that complete commissurotomy patients showed no performance decrement when required to simultaneously perform different or even opposite tasks with left and right hands whereas normal subjects had great difficulty making independent decisions for two simultaneously operating hands, displaying severe impairment of performance when required to do so. Sorting rates of control subjects varied significantly with each task condition such that Unimanual sorting was fastest followed by Bimanual-same, Bimanual-different and Bimanual-reverse. This pattern of effects led to a significant overall task effect [$F(3, 24) = -3.2$, $P < 0.001$] and group $\times$ task interaction [$F(3, 24) = 16.24$, $P < 0.001$] in a 2×4 (group $\times$ task) analysis of variance with task as a repeated measure computed on the right-handed sorting rates of controls and complete commissurotomy patients. An assessment of simple main effects verified that the significant task effect appeared only in control subjects [$F(3, 21) = 79.85$, $P < 0.001$]. A Newman–Keuls *post hoc* comparison of means showed that each mean differed significantly from each of the

others. Normal Ss sorted faster than split brain Ss in the Unimanual [t (1 tailed, 11 df) = 2.94, $P < 0.01$] and Bimanual-same [$t = 1.92$, $P < 0.05$] conditions with no differences between groups in the other conditions.

Figure 2 shows the sorting errors of each of the three groups tested under the four task conditions. Error rates are expressed as the percentage of total objects sorted by both hands combined which were placed in the incorrect compartment. A 2×4 analysis of variance between controls and complete commissurotomy patients again revealed a significant task

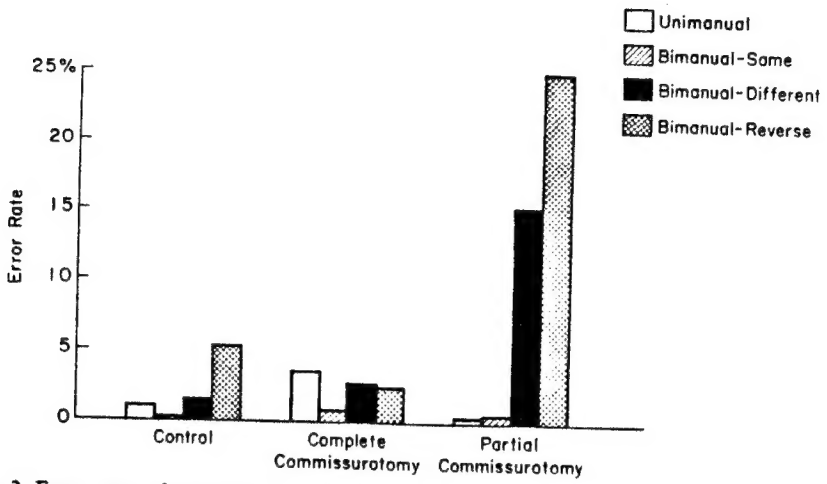

FIG. 2. Error rates of complete commissurotomy, partial commissurotomy and normal control subjects for four task conditions of Experiment I.

effect [F (3, 24) = 4.4, $P < 0.05$] and a significant group × task interaction [F (3, 24) = 3.1, $P < 0.05$] with the split-brain patients showing no difference between tasks while control subjects did show a significant task effect [F (3, 21) = 8.59, $P < 0.001$]. A Newman–Keuls procedure showed that this effect for normals was due entirely to the fact that significantly more errors were made in the Bimanual-reverse condition than in each of the other three conditions.

Like normal subjects, partial commissurotomy patients showed performance decrements in the Bimanual-different and Bimanual-reverse conditions. This was particularly evident with regard to error rate which increased markedly in both subjects, especially in the Bimanual-reverse condition. Both partial commissurotomy patients sorted more slowly and made more overall errors than either normal or complete commissurotomy subjects. This can be accounted for in part by established right-handed motor deficits in these patients [16], as well as a clinically apparent difficulty in comprehending instructions of the Bimanual-reverse and Bimanual-different tasks which may indicate greater cerebral dysfunction in these particular partial commissurotomy subjects.

Experiment II: Procedure

An unexpected and interesting finding in Experiment I was the significant difference normal Ss showed in both sorting and error rates between the Bimanual-different and the Bimanual-reverse conditions. Since complete commissurotomy patients performed these

two tasks with equal ease, each of the cerebral hemispheres appears to have considerable cognitive autonomy and to be equally proficient at both tasks. Only the unified attentional system of the partially and fully connected brain finds the Bimanual-reverse condition more confusing and difficult than the Bimanual-different. To ascertain the effectiveness of practice in leading to a possible lateralized division of attention in normal subjects, controls were given repeated trials under the two conditions. If the effect of practice is to increase the capacity for independent performance of the two simultaneous tasks, sorting and error rates in the Bimanual-reverse and Bimanual-different task conditions should be expected to become essentially identical for normal subjects as they were found to be for split-brain subjects. Conversely, if the effect of practice is merely to produce a quantitative increase in efficiency, performance on both tasks should improve at a comparable rate such that the Bimanual-different condition remains the easier of the two for normals.

The same eight control subjects who participated in Experiment I were subjects for Experiment II. Two testing sessions were used, separated by at least 48 hr. During a given session, subjects practiced either the Bimanual-different task or the Bimanual-reverse task with the order of task presentation counterbalanced. Subjects were told that they would be repeating a task they had done previously for five consecutive 3-min periods and that their goal was to increase speed and accuracy with each 3-min period. For added incentive to improve performance subjects were told that if their sorting was better than it had been during the session in which they originally performed the task, they would receive a $2.00 bonus.

After practice identical to that in Experiment I, subjects sorted for five 3-min periods. In the 30 sec interim between sorting periods, the experimenter replaced the filled side boxes with empty ones, replenished the central supply and encouraged subjects to improve during the next period. As subjects sorted, the experimenter counted objects placed in correct and incorrect compartments during the previous period.

Experiment II: Results

Figure 3 shows the mean number of beads sorted per minute during each 3-min period of the Bimanual-reverse and the Bimanual-different task conditions. The rates are for right hand only, since sorting rates for the two hands were the same, reflecting perfect maintenance of bimanual synchrony. All eight subjects are combined since the effect of order of task presentation was not significant. The results indicate that although improvement occurred steadily in the performance of both tasks over the five periods, rates on the Bimanual-reverse task showed greater gains, starting off below rates on the Bimanual-different task but catching up by the fifth period.

Figure 4 shows the mean error rate (percentage of total objects sorted which were placed incorrectly) of the two hands combined for each period of the Bimanual-different and

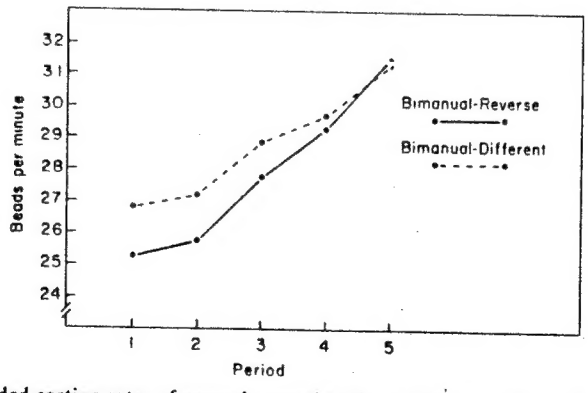

FIG. 3. Right-handed sorting rates of normal control subjects during consecutive 3 min periods of practice with the Bimanual-reverse and Bimanual-different task conditions in Experiment II.

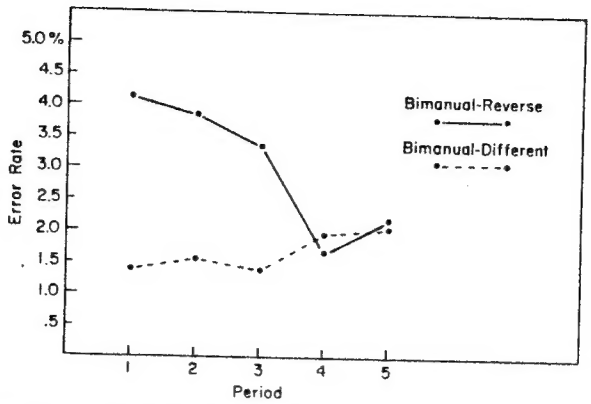

FIG. 4. Error rates of normal control subjects during consecutive 3 min periods of practice with the Bimanual-reverse and Bimanual-different task conditions in Experiment II.

Bimanual-reverse tasks. Error rates show differential practice effects for the two tasks which are even more dramatic than those for sorting rates. Errors in the Bimanual-reverse condition decrease markedly with practice to become equal to those in the Bimanual-different condition, where error rates tended to remain stable with practice.

A two-way (task × trial) repeated measures analysis of variance comparing objects placed correctly for period 1 and period 5 of the two task conditions indicated a significant trial effect, [F (1, 7) = 16.19, $P < 0.01$] as well as a significant task × trial interaction [F (1, 7) = 6.23, $P < 0.05$]. An analysis of simple main effects verified that although significant improvement with practice was evident for both task conditions, performance was significantly lower for the Bimanual-reverse condition during period 1, with greater improvement resulting in scores nearly identical to those of the Bimanual-different condition by period 5. Despite improvement with practice, sorting rates of normal subjects on both tasks during period 5 remained significantly below the Unimanual and Bimanual-same sorting rates they had shown in Experiment I.

DISCUSSION

The present findings support the idea that attention is normally limited to a unitary focus and that the cerebral commissures act to keep the left and right hemispheres working together in a single unified attentional system. This bilateral integration of attention appears to be a dominant organizing principle in cerebral function such that the intact hemispheres have great difficulty executing two simultaneous tasks independently despite lateralization of stimuli and responses. In the absence of the corpus callosum, complete commissurotomy subjects were able to voluntarily maintain independent attentional systems with lateralized information processing and decision-making mechanisms in left and right hemispheres. This divided attention was sustained for prolonged periods despite continual conflicting left and right motor activity as evidenced by the lack of appreciable differences between unimanual and bimanually incongruous sorting with respect to either speed or error rate. Partial commissurotomy patients, like normals, showed severe impairment of performance on dissimilar bimanual sorting tasks, indicating that the splenium alone is sufficient to insure the maintenance of attentional unity.

With extended practice, normal subjects achieved a qualitative enhancement of

performance which allowed simultaneously conflicting tasks to be carried out with less disruption in a manner behaviorally approximating that of split-brain subjects. This supports the hypothesis that in normal subjects practice altered performance such that the processing of separate tasks actually became simultaneous and independent rather than simply more efficient. Whether this alteration was brought about by the creation of two lateralized independent attentional systems as seen in split-brain patients, however, is questionable. Unlike three of the complete commissurotomy patients, normal subjects never broke bimanual synchrony during task performance. In addition, dissimilar bimanual tasks still produced performance decrements in normals after practice, yielding sorting rates significantly below unpracticed levels for bimanually identical or for unimanual tasks. Interhemispheric integration was further indicated by the fact that performance was often disrupted bilaterally when an error was made with either hand.

The observed improvement with practice in normals appears more readily interpreted as the result of a gradual automation of the task which increasingly freed performance from the need for attentional supervision. The enhanced performance following familiarity with a task has been explained by FITTS [19] in terms of three stages of perceptual–motor skill learning consisting of cognitions, fixation and automation. In the present results, the ability of normal subjects to effectively process multiple simultaneous inputs following automation of performance suggests that it is the involvement of focused attention which initially limits the performance of two tasks at once and that enhanced capacity for double performance coincides with decreased load on attentional mechanisms. The notion that attentional limitations to multiple channel processing can be circumvented via automation reconciles the present findings, along with other reports of simultaneous processing in normals, with the concept of an intrinsic unity of focus in mechanisms of attention.

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Résumé :

On a étudié chez 5 sujets avec commissurotomie complète, chez 2 avec commissurotomie partielle et chez 8 normaux le degré selon lequel est possible le maintien volontaire pendant une période prolongée, de systèmes attentionnels indépendants au niveau des hémisphères droit et gauche pendant des performances simultanées latéralisées. Les sujets accomplissaient une tâche uni-manuelle tactile de classement de même qu'une tâche bi-manuelle réclamant des décisions par l'hémisphère droit et par l'hémisphère gauche : identique, différent, simultanément opposé. On donnait aux sujets normaux des sessions d'entrainement avec les mêmes tâches dans le but de déterminer les limites de la capacité de double traitement. Ces résultats suggèrent que les commissures cérébrales obligent les 2 hémisphères à travailler ensemble et maintiennent alors l'unité attentionnelle dans le cerveau intact. La pratique chez les normaux augmente la capacité de traitement simultané mais cette augmentation est plus aisément interprétée comme le résultat d'une automatisation d'une performance diminuant les besoins de supervision attentionnelle que comme une division de l'unité normale de fixation d'un système attentionnel intact.

Zusammenfassung

Das Ausmaß, in welchem unabhängige Aufmerksamkeitssysteme in der linken und in der rechten Hemisphäre während lateralisierter doppelt-simultaner Leistungen ihre willkürliche Tätigkeit für ausgedehntere Perioden aufrecht halten können, wurde an 5 Patienten mit vollständiger Kommissurotomie, 2 Patienten mit partieller Kommissurotomie und in 8 gesunden Versuchspersonen untersucht.

Die Versuchspersonen führten eine einhändige taktile Sortieraufgabe und bimanuelle Sortieraufgaben aus, welche gleichartige, unterschiedliche und entgegengesetzte gleichzeitige Entscheidungen der linken und der rechten Hemisphäre verlangten. Die gesunden Versuchspersonen bekamen zusätzlich Übungssitzungen mit denselben Aufgaben, um die Grenzen der Kapazität für die beidseitige Informationsverarbeitung festzustellen. Die Ergebnisse legen die Annahme nahe, daß die Großhirnkommissuren die beiden Hemisphären zwingen, zusammen zu arbeiten, um im intakten Gehirn einheitliche Aufmerksamkeit aufrecht zu erhalten. Übung verstärkt die Fähigkeit für gleichzeitige Verarbeitung von Stimuli bei Gesunden, aber diese Verstärkung kann am einfachsten als das Ergebnis von Automation der Ausführung interpretiert werden, durch welche die Notwendigkeit für die Kontrolle durch die Aufmerksamkeitsmechanismen vermindert wird. Diese Interpretation liegt näher als die einer Teilung der normalen Zentrierung der intakten Aufmerksamkeitssysteme.